P041

Small Scale Modeling, a Tool to Assess Subsurface Imaging Methods - Application to Seismic Full Waveform Inversion

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SUMMARY

Imaging of the first meters of the subsurface with seismic methods is useful for civil engineering and landscape management. Seismic Full Waveform Invertion (FWI) is an imaging method that offers relevant performances to image heterogeneous media like subsurface by taking into account the whole waveform all kind of waves. But heterogeneity, attenuation and variability of near surface make difficult the adaptation of seismic imaging methods at this exploration scale. In order to evaluate performances of FWI on subsurface applications, we perform small scale physical modeling by using laser ultrasonics. Combined approach with numerical simulations and small scale measurements is used to study behavior of FWI on simplified models of the near surface. Accurate seismic data are obtained in fully controlled experiments on reduced scale modeling of underground cavity detection. Elastic waveform inversion on a numerical case and with a small scale experimental data set are presented in this paper. We show how FWI can quantitatively image low velocity heterogeneities whereas high contrast objects or void are only partially imaged.

Introduction

Imaging the first meters of the subsurface with seismic methods is useful for civil engineering and landscape management. But heterogeneity and strong attenuation of the near surface can make difficult the adaptation of deep seismic imaging methods at this exploration scale. Moreover, the large variety of applications and the uniqueness of soils properties in each cases make hazardous the evaluation of the limits of imaging technics. For those reasons we have performed physical modeling at reduced scale by using a non-contact ultrasonic laboratory using laser interferometry to assess the performances of seismic methods in fully controlled experiments. While it takes into account the whole waveform of all kind of waves propagating in the medium, seismic Full Waveform Inversion (FWI) is a quantitative imaging method which offers relevant performances to image heterogeneous media like subsurface. Characterisation of underground cavities and foundations are important issues we are interested in. Gelis (2005) introduced surface waves in her waveform inversion algorithm and successfully applied it to underground cavity detection in numerical experiments but failed to interpret results in a real experiment because of the complex and uncontrolled environement and of an unadapted measurement configuration. In this paper, we show how combination of physical and numerical simulations can help to validate and calibrate FWI for high contrast object detection. After a brief review of FWI principle and application on a numerical case, we detail the principles of the laboratory modeling and present the data recorded in a model simulating the presence of an underground cavity. FWI is applied to this data and results are discussed.

Full Waveform Inversion applied to subsurface

Most of the conventionnal seismic methods are based on the exploitation of only a part of the information present in the data (e.g. traveltimes in tomography or migration). That means information contained in the amplitudes is neglected. Furthermore, depending on the method, only one kind of wave is generally considered. Near surface is a strongly heterogenous and attenuating medium where data are often dominated by powerfull dispersive surface waves making time informations difficult to pick. The use of a more complete method taking into account both phase and amplitude of all kind of waves should enhance subsurface imaging.
FWI is an iterative multi-parameter quantitative imaging method developed to obtain high resolution images of natural underground media by back propagating data residuals and correlating them with forward modeling wavefields. In frequency domain FWI (Pratt and Worthington, 1990), the forward problem, which is highly non linear, consists in the calculation of the wave field $g(\mathbf{m})$ at each point of a model of parameter $\mathbf{m}$ representing the heterogeneous medium with a numerical method (e.g. finite difference, finite volume) for one particular frequency. Resolution of such a non linear inverse problem is usually performed by an iterative local minimisation of a cost function depending on the difference between data calculated and observed at each receivers points :

$$C(\mathbf{m}) = \frac{1}{2}\left(\mathbf{d_{calc}}(\mathbf{m}) - \mathbf{d_{obs}}\right)^t \left(\mathbf{d_{calc}}(\mathbf{m}) - \mathbf{d_{obs}}\right)^* \tag{1}$$

At each iteration k, $C(\mathbf{m})$ is linearized around a model $\mathbf{m^k}$ and a new model of parameter is obained by :

$$\mathbf{m^{k+1}} = \mathbf{m^k} - (\Re[F^t F^*])^{-1}(\Re[F^t \mathbf{\Delta d_k}^*]), \tag{2}$$

where the Frechet derivate is defined as the partial derivative $F = \partial g(\mathbf{m})/\partial \mathbf{m}$ at the model $\mathbf{m^k}$. After complete optimisation, the obtained model is re-used as an initial model to invert data for an other frequency.

Two synthetic experiments of acoustic waveform inversion are realised with a 3 layers model whose P-wave velocities are 1500, 1650 and 1800 m/s with an inclusion in the highest layer presenting respectively a low and a high velocity contrast (respectively 1700 and 5000 m/s). Such a model should be representative in size and contrast of a rigid foundation in his low velocity weathered zone. Forward and inverse computations are performed using the algorithm of Sourbier et al. (2008). Forward model is calculated over a finite difference grid which contains 100 x 294 points. 100 receivers and 10 sources are evenly positioned along the surface. Six frequencies (from 100kHz to 650kHz) are successively inverted proceeding from the low to the high frequencies as recommend by Sirgue and Pratt (2003). At each frequency inversion, 3 iterations were performed. Figures 1 a and b show respectively the true model and the initial model which contains the low frequency information of the image. Final recovered images for the two different inclusions are presented on Figures 1 c and d, and corresponding velocity profiles on Figures 1 e and f. Velocities in the layers and interfaces are accurately recovered. Inclusion is well localized in both cases. Velocity in the low contrast inclusion is determined with a maximum error of 50m/s, but even with more iterations, inversion fails to exactly reach the true value for the high contrast inclusion (2600m/s instead of 5000m/s). This error and the artefacts observed all around the inclusion are due to the necessity to image high contrasts whereas linearisation of the inverse problem is done with a Born approximation, and so is correct only for low distance between initial and true model. Other numerical experiments had confirmed that for the same reason, the misfit of FWI to image a void is also important, exacerbated by the fact that seismic waves are not supposed to propagated through a void.

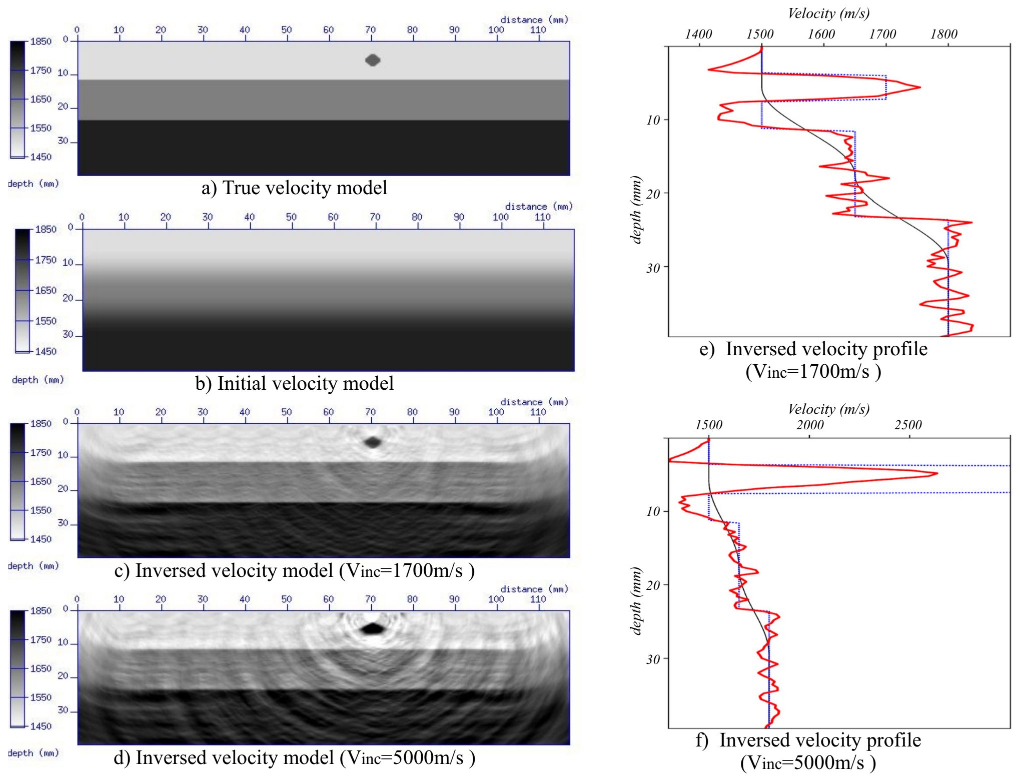

Figure 1: Acoustic waveform inversion in a synthetic case

Small scale modeling of underground cavity caracterisation

In order to realise a complementary numerical and physical approach on those subsurface problems, a laboratory of controled experiment at ultrasonic scale had been comissioned. Small scale physical modeling allows to study propagation phenomenons or imaging methods with experimental data at centimetric dimensions, independently of the numerous unknown parameters like true medium properties, receiver coupling or generated waveform. Ultrasonic physical modelisation has already been used by a few geophysicists to evaluate performances of imaging methods (e.g. Isaac and Lawton, 1999; Pratt, 1999; Bodet et al., 2005). Non contact technics like laser has been used to study surface waves but never to modelise seismic reflection or transmission configurations. Our laboratory (Figure 2 a) performs non contact surveys using a Bossa Nova® laser interferometer to record absolute normal particle displacement at the surface. Generation of ultrasonic waves with controlled coupling and conservation of the source wavelet is performed by a piezoelectric contact transducer enhanced with an adaptator allowing ponctual coupling (Figure 2 b). Source and receiver can be automatically moved over the surface with a positionning accuracy of 0.01mm. The acquisition chain is able to measure signals from 30kHz to 2MHz coded over 16bits with a noise level inferior to 0.5Å. Transmission as well as reflection surveys are possible.

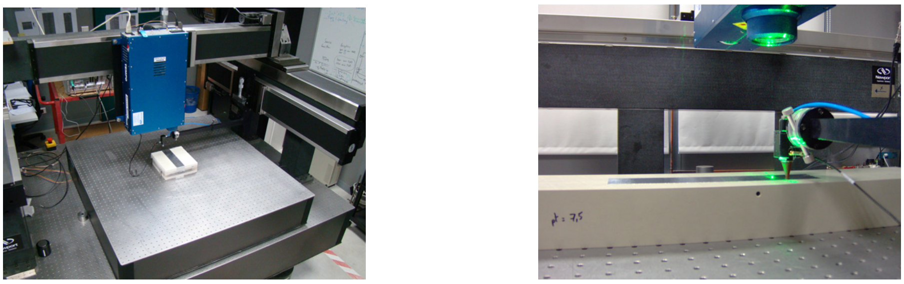

Figure 2: Small scale seismic laboratory (a). Acquisition of data on the cavity model (b)

In order to simulate underground cavity, acquisition of seismic data with 25 sources and 241 receivers positions is realised over a polypropylen model (Vp=2750m/s, Vs=1225m/s) with a cylindrical void (Figure 2 b). Signal is centered around 500kHz. The dimensions of the void compared to the wavelengh (diameter about one wavelength and depth at two wavelength from the surface) are typical of a cavity which could be difficult to image (e.g. diameter 5m at 10m depth). Synthetic data calculated with the elastic finite volume code developped by Brossier et al. (2008) and small scale experiment data are compared Figure 3 a and b. Both seismograms exhibit accurate similar behaviors with direct P-wave (1), surface waves (2), diffracted P-wave (3) and surface wave converted diffraction (4).

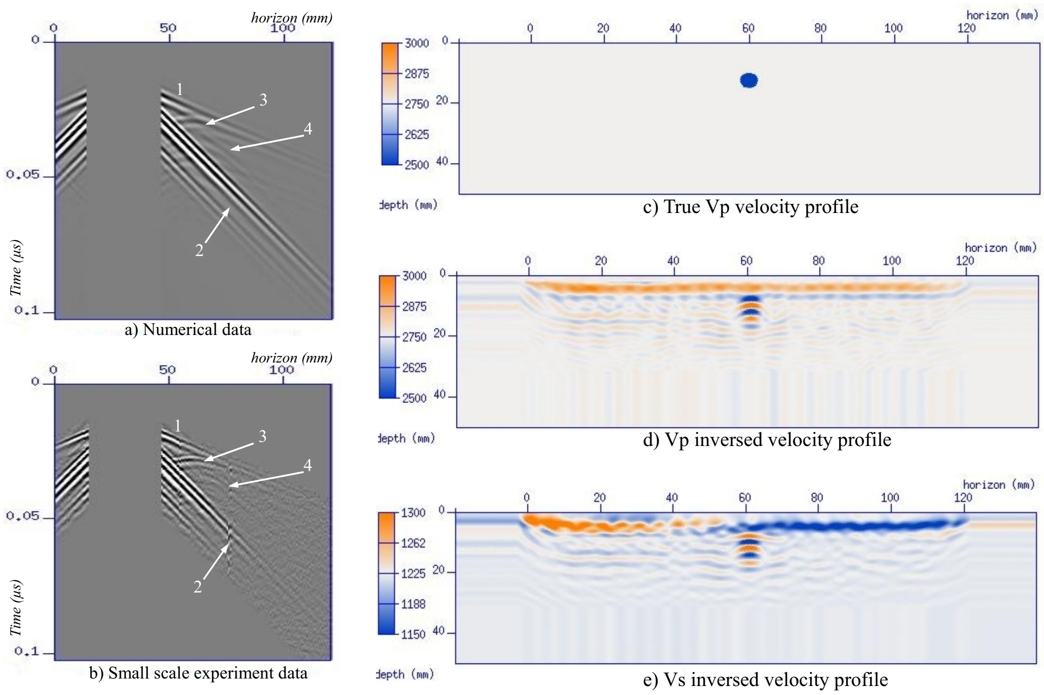

Figure 3: Inversion of small scale data from the underground cavity model : Time seismograms and velocity profiles

Small scale data are inversed with an elastic full waveform inversion algorithm taking into acount surface waves. We use no more preprocessing operations than muting the empty traces and the latest arrivals due to reflexions on the edges of the small scale model. Void is not a favorable case for FWI, so in order to reduce artefacts and because target is alone, all the frequencies of the data are inversed simultaneously (50 freqencies from 200 to 700kHz). As shown in previous part, inclusion is localised in Vp and Vs profiles, at least in the horizontal direction, but important artefacts are still disturbing geometrical caracterisation of the inclusion particularly in the vertical direction (Figure 3 c, d, e). The bad quality of the recovered form of the inclusion is mostly due to the same reason as in previous experiment, nevertheless the information missing on large offsets because of strongh attenuation (Q<20) could be helpful to get a better image of the deepest part of the cavity. Presence of a reflector under the cavity may also contribute to illuminate its hidden side.

Conclusions

An ultrasonic laboratory has been designed to perform seismic measurements in fully controled conditions. First data and inversed results obtained on the laboratory were presented. It has been shown that combination of small scale data with with numerical simulation is an essential tool to study imaging methods like waveform inversion in simplified conditions and so to quantify the influence of the imaging parameters on subsurface applications. Experiments shows that FWI is able to accurately image low velocity perturbations whereas in case of high contrast object, only the geometry is recovered.

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